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ENVIRONMENTAL TOXICOLOGY AND BIOGEOCHEMISTRY OF ECOSYSTEMS

# An environmental assessment model of construction and demolition waste based on system dynamics: a case study in Guangzhou

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**Abstract**
At present, China is in the rapid development stage of urbanization, and construction activities are becoming more frequent. This is accompanied by a large amount of construction and demolition waste (C&DW), which raises many problems with its governance, such as occupying valuable land resources, causing air pollution, and consuming raw materials. In this study, taking Guangzhou as an example, the system dynamics principle was used to establish an environmental assessment model of C&DW, and Vensim software was used to simulate and analyze the environmental, economic, and social impacts of various disposal methods of C&DW. The results showed that (1) among all waste disposal methods, landfill disposal had the highest greenhouse gas emissions. It was estimated that the greenhouse gas emissions from landfill disposal will account for 75% of the total emissions in 2030, while the greenhouse gas emissions from recycling disposal will only account for 0.5%. (2) The simulation results showed that, according to the current data, the land area occupied by waste landfills and illegal dumping in 2030 will be about 4.88 million $m^2$, and the economic loss caused by land loss and global warming will account for 9.1% of Guangzhou's GDP in 2030, which is equivalent to the national economy of a regional city with a less developed economy. (3) Enhanced supervision could significantly reduce the amount of illegal dumping, but its effect on landfill disposal and recycling would be very limited. According to the results of the simulation analysis, some suggestions were put forward to improve the environmental, economic, and social impact of C&DW disposal in Guangzhou.

**Keywords** Construction and demolition waste · Environmental assessment · System dynamics · Greenhouse gas emissions

## Introduction

With the continuous advancement of China's urbanization process and the rapid growth in the national economy, China's comprehensive national strength has significantly increased, and people's standard of living has generally reached a comfortable level. However, environmental problems generally accompany economic growth. As the main pillar of the national economy, the construction industry has been developing rapidly. A large amount of construction and demolition waste (C&DW) has been produced owing to the continuous increase in new buildings, building renovations, reconstruction, repairs, demolition, and construction projects and infrastructure projects. According to statistics, the newly completed areas in China cover 2 billion $m^2$/year, which is close to half of the global construction area, and will continue to grow. It is estimated that the newly added construction area will cover about 30 billion $m^2$ by 2020 (Yang and Ma 2009; Liu et al. 2019). Guangzhou, which is an economically developed city, has an annual construction area, newly completed area, and waste output as shown in Fig. 1. In recent years, the recycling rate of C&DW in Guangzhou has only been 65%, while that in developed countries was 90%(Hu et al. 2016). In the Netherlands, the recycling rate of C&DW was as high as 95% in 2001 (NEAA 2010). The high recovery rate can not only produce clear environmental benefits but also obtain considerable economic benefits through resource reuse. In contrast, the utilization rate of C&DW in China is relatively low, which also reveals that the level of waste management in China needs to be improved urgently. If the contractor fails to properly dispose of C&DW, then a large amount of waste not only occupies valuable land resources and destroys the soil structure, but also

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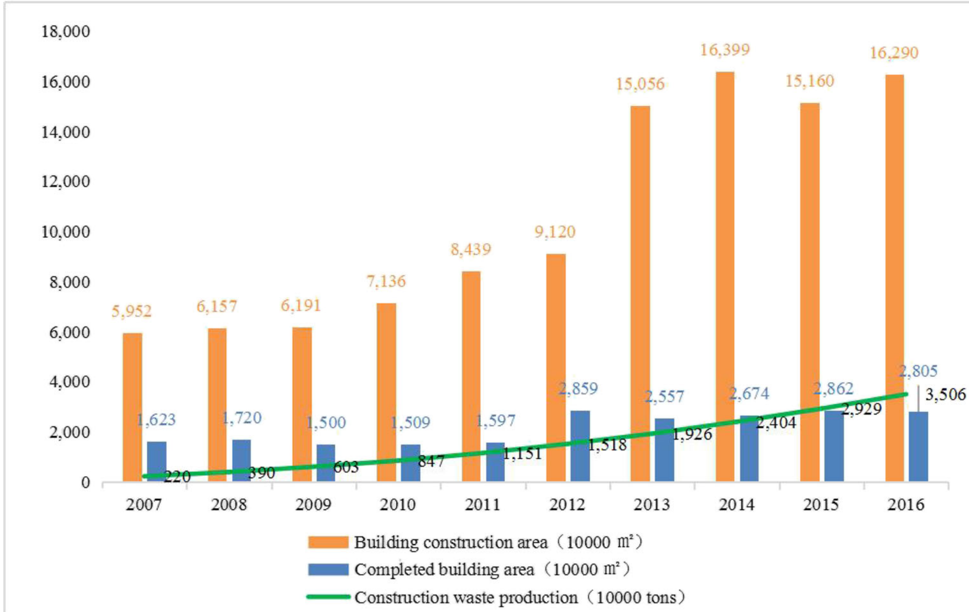



**Fig. 1** Annual construction area and annual construction and demolition waste production (GBS 2017)

emits a large amount of greenhouse gases, which cause air pollution lead to global warming, and eventually destroy the environment in which people live and endanger their health (Liao et al. 2017a; Liao et al. 2017b; Liao et al. 2018). Therefore, how to implement effective C&DW management, improve the recycling rate of C&DW, and reduce the environmental impact of C&DW disposal have become urgent problems that need to be solved.

The disposal methods of C&DW can be roughly classified into four types, namely reuse, recycling, incineration, and landfilling. Landfilling is the main disposal method of C&DW in China, and incineration is seldom used. C&DW can cause air pollution and aggravate global warming. Studies have shown that landfills produce about 91 kg of greenhouse gases per ton of waste (Marzouk and Azab 2014). Therefore, it is difficult to meet the policy of urban sustainable development by means of landfill and so on after the generation of C&DW. From the perspective of government departments, China's management of C&DW mainly focuses on economic evaluation, and there is relatively little emphasis on environmental assessment, especially analysis of the combination of the environment, economy, and society. In this study, from an environmental point of view combined with an economic and social, by studying the process of C&DW disposal, this paper analyzes the environmental pollution, economic impact, and social benefits of C&DW resource disposal, and takes Guangzhou as an example to simulate the impact of greenhouse gas emissions from C&DW disposal on the environment and the economic losses caused by the method of system dynamics, and to make a strategic choice according to the comprehensive benefits of the way of resource disposal. The most effective environmental benefits of C&DW disposal methods were determined, which could provide feasible suggestions to relevant government departments for the recycling of C&DW.

## Literature review

In recent years, environmental problems caused by C&DW have become increasingly prominent. The government has begun to pay attention to the environmental impact of C&DW. In addition, the economic benefits of recycling and utilizing C&DW have attracted the attention of contractors and developers. Many scholars have begun to focus on the reduction management of C&DW. In China, the reduction management of C&DW and its environmental impact have also attracted the attention of many scholars. Through Vensim software modeling and simulation of actual data in Shenzhen, Wang et al. (2016) concluded that the environmental impact cost of landfilling C&DW would increase yearly from 2015 to 2024, and that the environmental impact of fuel energy consumption and land occupation would account for 88.67% of the environmental impact of C&DW landfill disposal according to the data at the end of the simulation period in 2024. Ding et al. (2016) used system dynamics (SD) and the theory of planned behavior to establish a dynamic model of C&DW reduction management. The results showed that reduction management could effectively reduce 27.05% of the waste production, alleviate the pollution damage of waste to the environment, and reduce the total cost of waste management. Liu et al. (2018) used SD to model and simulate the environmental benefits of C&DW recycling through literature analysis, field research, and questionnaires. Through scenario analysis of an environmental benefit model, it was concluded that reasonable penalties for illegal discharge units, unit landfill fees, the distance from C&DW to resource disposal centers, and unit subsidies for resource utilization could improve the environmental benefits. Wang et al. (2018a, b) combined life cycle assessment (LCA) with building information modeling to study a high-rise residential building. The results showed that the environmental benefits of recycling C&DW varied with the materials. In addition, on-site recycling of waste could reduce carbon emissions more effectively than factory recycling and waste landfilling. Hossain et al. (2017) used the LCA method to comprehensively evaluate the environmental performance of the C&DW management system in Hong Kong based on the actual data and documentary data of two construction sites there, and found that the C&DW management system based on off-site sorting and direct landfilling had a significant impact on the environment, but through the on-site sorting system, considerable net environmental benefits could be achieved. Wang et al. (2018a, b) used the LCA and willingness to pay methods to investigate the environmental impact of recycling 1 t of demolition waste in Shenzhen. The environmental impacts included global warming, ozone depletion, acidification, eutrophication, suspended particulate matter, solid waste creation, and land consumption. The results showed that recycling could provide an environmental benefit of 1.21 CNY/t environmental benefit, while the environmental cost of direct landfilling was 12.04 CNY/t. The impact of environmental assessment on C&DW disposal in China is shown in Table 1.

The environment for recycling C&DW has also attracted the attention of many scholars abroad. Marzouk and Azab (2014) used STELLA software to create a dynamic model of C&DW management. The research showed that recycling and utilizing C&DW could not only significantly reduce greenhouse gas emissions, energy use, and waste landfill space, but also reduce the global warming potential. Marrero et al. (2017) established a complete waste quantification model based on the work breakdown system of the project budget on the basis of previous research. By evaluating five urbanization projects, two industrial projects, and three residential projects, the waste quantity, budget, and ecological footprint were determined. The study showed that 98% of waste is produced by earthworks and tree felling and that 97% of the ecological footprint is caused by fuel consumed by on-site machinery and building materials. A new scheme for 100% soil reuse and crushing of inert waste as concrete aggregate was proposed. In all the cases analyzed, the ecological footprint value was reduced by more than 20%. They also showed that it was feasible to quantify the overall impact of building engineering application recovery and reuse strategies using a work breakdown system. Finally, from the perspective of construction projects, the traditional waste management and economic control model could be completed by using ecological footprint indicators for environmental analysis. Alba-Rodríguez et al. (2017) established a comprehensive model to conduct technical, economic, and environmental assessments of buildings facing demolition or renovation. The feasibility of building renovation was analyzed as a whole. By evaluating the proposed interventions, strategies to reduce the economic and environmental impacts of various activities could be identified. In order to assess the net carbon, energy, and water footprints of recycling and other waste management alternatives, and to track the impact of three waste management modes (recycling, landfilling, and incineration) on the entire economic supply chain, Kucukvar et al. (2014) developed a mixed LCA model based on economic input and output. The results showed that only the recycling of building materials could have a positive impact on the environmental footprint in terms of carbon, energy, and water footprint, and incineration was a better alternative after the water and energy footprint categories were recovered. Landfilling was considered a slightly better strategy when the carbon footprint was the main focus. Colangelo et al. (2018) used the LCA method to compare and analyze four different concrete mixtures, namely, C&DW, incinerator ash, marble sludge and blast furnace slag. In this study, the use of “green” recycled aggregates in concrete production was proposed to facilitate the assessment of potential adverse effects from an environmental and energy perspective and to analyze them using SimaPro(C) software. It was concluded that the recycled aggregate was better than traditional concrete. Among the recycled aggregates, the blast furnace slag had the least impact on the environment. Rodríguez et al. (2007) introduced the evaluation results of waste management in the Madrid Autonomous Region based on collection, statistical disposal, and analysis; compared the site management with and without the environmental management system; and analyzed the effectiveness of waste management and the current environmental management system, in order to understand the deficiencies in environmental management systems and existing waste management systems and identify environmental management measures in all primary areas to promote the recycling and recycling management of C&DW by construction companies. The impact of environmental assessment on C&DW disposal abroad is shown in Table 2.

From the above analysis, scholars have different perspectives on environmental impact analysis of recycling management of C&DW. In China, some scholars used SD to analyze the environmental benefits of landfilling, source reduction, and resource-based disposal of C&DW; others used the life cycle method to assess the environmental impact and economic benefits of carbon emissions from C&DW. For the environmental benefits of recycling management of demolition and C&DW, foreign scholars have different research perspectives. Some foreign scholars analyzed the environmental benefit and economic impact of C&DW from the perspective of the carbon and ecological footprints by establishing an environmental assessment model of C&DW. Others concluded that the

**Table 1** Environmental study on construction and demolition waste (C&DW) disposal in China

| Scholars | Theory/research method | Research direction | Conclusions |
|---|---|---|---|
| Wang et al. 2016 | Vensim software modeling | Environmental impact of C&DW landfill | The environmental impact cost of C&DW landfilling is increasing each year. The environmental impact of fuel energy consumption and land occupation accounts for 88.67% of the environmental impact of C&DW landfill disposal. |
| Ding et al. 2016 | SD and theory of planned behavior | Environmental benefits of C&DW reduction management | Reduction management of waste sources can effectively reduce 27.05% of waste production, alleviate landfill pressure, save land resources, reduce waste disposal costs of construction enterprises, produce environmental benefits, and effectively reduce environmental pollution problems caused by C&DW. |
| Liu et al. 2018 | SD, literature analysis, field research, and questionnaires | Environmental benefits of C&DW resources | Establishing reasonable penalties for illegal discharging units, unit landfill fees, the distance from C&DW to resource disposal centers, and unit subsidies for resource utilization have a greater, positive impact on environmental benefits. |
| Wang et al. 2018a, b | LCA and building information modeling | Demolition waste carbon emissions | The environmental benefits of recycling and utilization of C&DW vary depending on the material. Compared with brick and stone wastes, recycling and utilization of metal wastes have greater environmental benefits. Carbon emission reduction of aluminum is as high as 45%, but only 0.66% of the total weight. In different life cycle stages, on-site collection and classification are the largest contributors to total carbon emissions. Compared with factory recycling and landfilling, on-site recycling is more conducive to reducing carbon emissions. |
| Hossain et al. 2017 | LCA | Impact of different waste sorting systems on the C&DW management environment | Off-site sorting and direct landfill C&DW management systems have a significant impact on the environment. The net environmental benefits of on-site sorting systems are considerable; the environmental benefits are mainly determined by the composition and classification management of wastes. Metal recycling can reduce greenhouse gas emissions and replace iron ore to produce new steel. |
| Wang et al. 2018a, b | LCA and willingness to pay | Environmental costs and benefits of C&DW | Recycling 1 ton of demolition waste can provide 1.21 CNY of environmental benefits; the current fees for landfills are not high enough to offset the environmental costs, the construction and operation costs and potential fines for landfills. |

recycling of building materials and effective environmental management systems have positive effects on improving environmental management while avoiding unnecessary economic losses caused by the waste of resources through LCA, collection, and statistics. It can be seen from the analysis that scholars within China and abroad mainly study the resource management of C&DW from the perspective of the environment or economy, but seldom combine the three aspects of environment, economy, and society. In this study, from the point of view of the environment combined with the economy and society, the environmental pollution and economic impact of C&DW disposal methods were analyzed by studying the process of C&DW disposal. Moreover, taking Guangzhou as an example, the SD method was used to simulate the impact of greenhouse gas emissions on the environment and the economic losses caused by different disposal methods of C&DW, and some suggestions for low-carbon C&DW disposal were introduced.

## Research methods

SD is a science that was founded by Professor Jay Forrester of the Massachusetts Institute of Technology in 1956 to study the dynamic complexity of systems. It is based on feedback control theory and computer simulation technology and is mainly

**Table 2** Environmental study on construction and demolition waste (C&DW) disposal abroad

| Scholars | Theory/research method | Research direction | Conclusions |
|---|---|---|---|
| Marzouk and Azab 2014 | STELLA software modeling | Environmental impact of C&DW | Recycling and utilizing demolition waste can not only significantly reduce greenhouse gas emissions, energy use, and waste landfill space, but also reduce the global warming potential. |
| Madelyn et al. 2017 | Establishing a quantitative waste model based on an engineering budget work decomposition system | Ecological footprint of waste | Fuel consumption of on-site machinery and building materials cause 97% of the ecological footprint. A new scheme using 100% soil and crushing inert waste as concrete aggregate was proposed. In all cases, the ecological footprint value was reduced by more than 20%. From the perspective of construction projects, the traditional waste management and economic control model can be completed by using ecological footprint indicators for environmental analysis. |
| Alba-Rodríguez et al. 2017 | Establishing a comprehensive assessment model for C&DW | Technological, economic, and environmental assessment of C&DW | The technical, economic, and environmental assessment of the restoration of buildings facing demolition or new construction was conducted. The feasibility of the restoration of buildings was analyzed as a whole. Through the evaluation of the proposed interventions, strategies for reducing the economic and environmental impacts of various activities were determined. |
| Kucukvar et al. 2014 | Creating a mixed LCA model based on economic input-output | Assessment of the environmental impact of alternative C&DW management methods using supply chain life cycle analysis | Only the recycling of building materials could have a positive impact on the environmental footprint in terms of carbon, energy, and water. Incineration is a better alternative after water and energy footprint categories are recovered, and landfilling is considered a slightly better strategy when carbon footprint is the main focus. |
| Colangelo et al. 2018 | LCA and SimaPro(C) software | Environmental assessment of different concrete mixtures | Compared with traditional concrete, recycled aggregate has better performance, and blast furnace slag has the least impact on the environment. Production of ordinary Portland concrete in Campania, Italy, is related to high carbon dioxide emissions. The use of recycled aggregates can ensure the reduction in global warming. The use of recycled aggregates can improve environmental management issues. |
| Rodríguez et al. 2007 | Collection, statistical processing, and analysis | Environmental management system for C&DW | Comparing the situation of the construction site with or without an environmental management system, it is concluded that the application of the environmental management system in the construction site will help to gradually improve the environmental awareness of all staff members. At the same time, defects in the environmental management system and improvement measures are found. |

used to study the relationship between the structure, function, and dynamic behavior of complex systems (Yuan and Zhang 2010). C&DW management is a complex system, involving many stakeholders and links. It requires the joint efforts of the government, environmental protection departments, building materials departments and construction units, as well as other relevant departments. It is reasonable to use SD to solve the related problems of C&DW management.

## An environmental assessment system for C&DW

At present, there are four typical methods of C&DW management, namely illegal landfilling, simple landfilling, resource-based disposal, and on-site resource utilization, from which the status of domestic and foreign C&DW resource management is understood, the commonalities and differences in the development of resource management are comprehensively analyzed, and the current situation of C&DW reduction management in Guangzhou is understood based on the existing literature and field research. A research system model was determined according to the actual situation in Guangzhou. As shown in Fig. 2, the model was constructed and simulated according to the program in the figure.

The environmental assessment model of C&DW established in this study had three main purposes. (1) According to Vensim causal cycle diagram, a comprehensive and systematic description of the logical relationship and interaction between factors will help the relevant personnel to better understand the changes in the whole system caused by changes within the system. (2) By simulating and analyzing

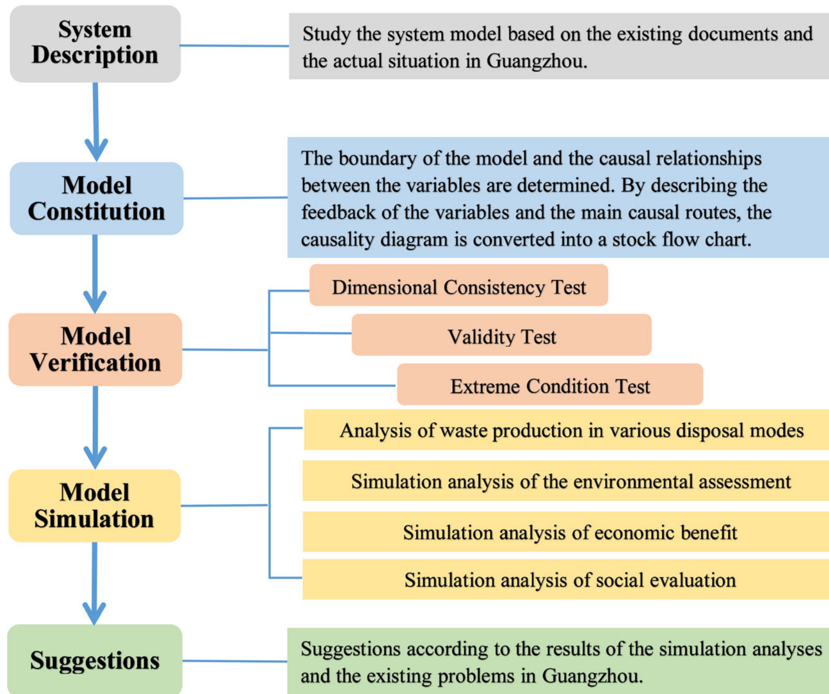



**Fig. 2** Research system framework

the output of C&DW in Guangzhou through the SD model, the environmental impact of greenhouse gas emissions from various disposal methods of C&DW was analyzed, and low-carbon emission reduction measures were taken to improve it. (3) Based on the model simulation results, the environmental, economic, and social impacts of C&DW management processes were analyzed, and suggestions were introduced to improve the existing problems in the disposal process.

## Causal feedback diagram for the environmental benefit assessment of C&DW

There are many factors affecting the recycling of C&DW, including environmental, economic and social aspects, which are interrelated and mutually influential, as shown in Fig. 3.

The disposal methods of C&DW include illegal dumping, landfilling, and recycling, which involves the generation of C&DW, illegal landfilling, landfill disposal, recycling, and recycling costs, among others. Based on this framework, according to the environmental benefit evaluation indicators (energy consumption, greenhouse gas emissions, and land, social, and economic losses), the intermediate variables of each indicator and the factors affecting the intermediate variables were derived. The environmental benefit evaluation model was established by the environmental benefit evaluation indicators, intermediate variables, and the factors affecting the intermediate variables. Through the analysis of the environmental impact of the disposal methods of C&DW, the interaction among the factors in the waste environmental assessment system were obtained, and a causality diagram of the waste environmental assessment system was created, as shown in Fig. 4.

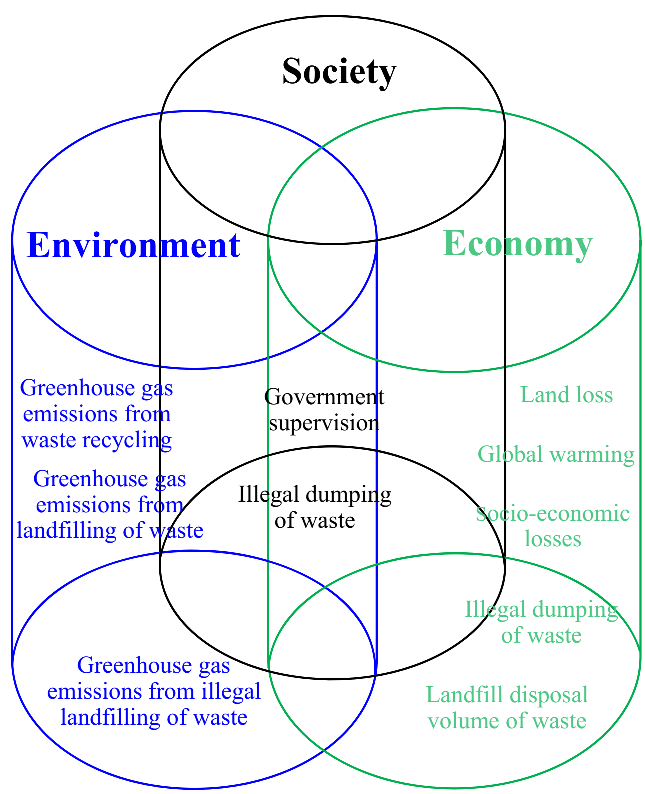



**Fig. 3** Environmental, economic, and social factors

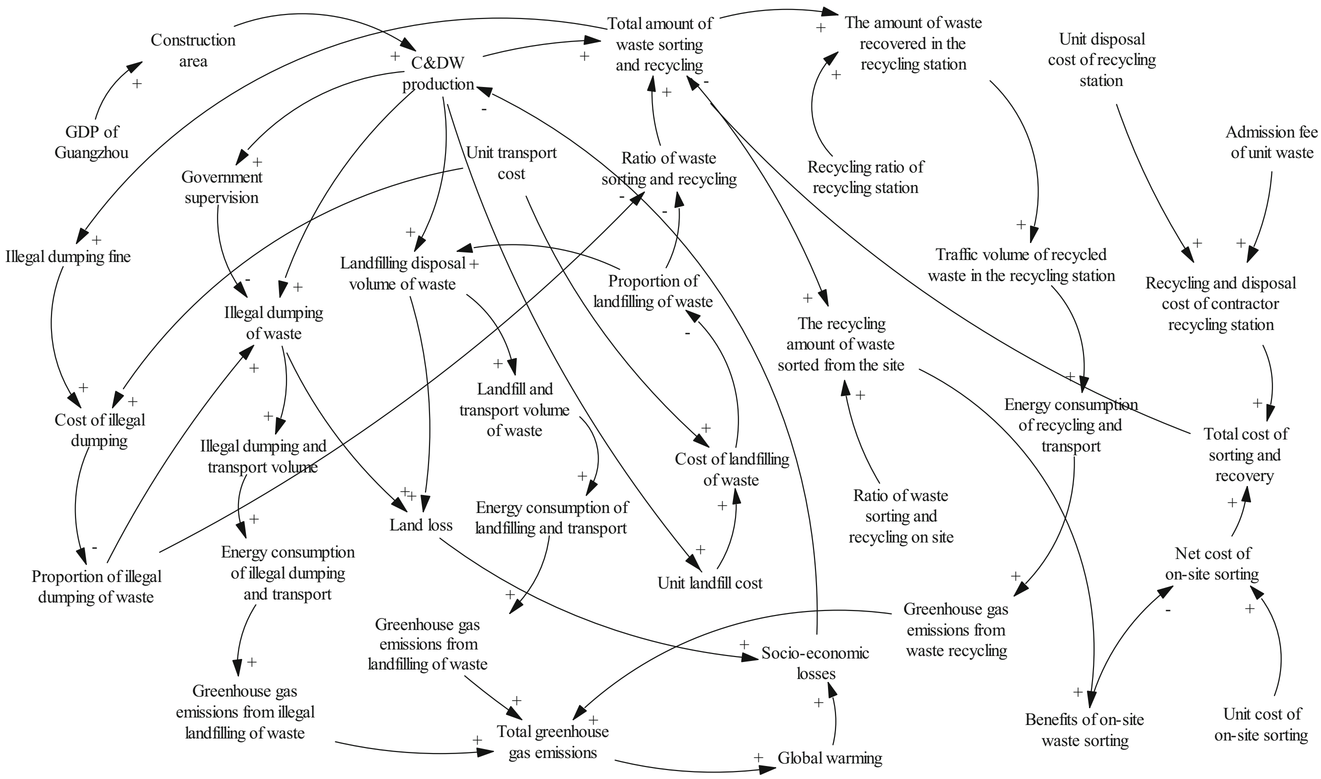



**Fig. 4** Causality diagram for the environmental assessment system of construction and demolition waste

## Environmental benefit analysis

The main routes affecting environmental benefits are as follows:

R1: C&DW production→Illegal dumping of waste→Illegal dumping and transport volume→Energy consumption of illegal dumping and transport→Greenhouse gas emissions from illegal landfilling of waste→Total greenhouse gas emissions→Global warming→Socio-economic losses→C&DW production.
R2: C&DW production→Landfill disposal volume of waste→Landfill and transport volume of waste→Energy consumption of landfilling and transport→Greenhouse gas emissions from landfilling of waste→Total greenhouse gas emissions→Global warming→Socio-economic losses→C&DW production.
R3: C&DW production→Total amount of waste sorting and recycling→The amount of waste recovered in the recycling station→Traffic volume of recycled waste in the recycling station→Energy consumption of recycling and transport→Greenhouse gas emissions from waste recycling→Total greenhouse gas emissions→Global warming→Socio-economic losses→C&DW production.

The three causal feedback routes of R1, R2, and R3 express the process of greenhouse gas production from C&DW. A large amount of C&DW is produced during construction. The main methods to deal with this waste are illegal landfilling, landfilling, and recycling. In addition, the transport and disposal of these wastes will consume energy, generate greenhouse gases, pollute the air, and increase the potential of global warming. A large amount of greenhouse gas emissions will seriously pollute the environment and lead to global warming, thereby affecting human survival and economic development and causing social and economic losses. In order to reduce environmental pollution and economic losses, relevant government departments must take measures to minimize the production of C&DW.

## Economic benefit analysis

The process of urbanization will inevitably be accompanied by the emergence of new buildings, the demolition or renovation of old buildings, and a large amount of waste, thereby resulting in the waste of resources, environmental pollution, and other issues that will seriously hinder the sustainable development of cities and result in economic losses (Xiao et al. 2019). The causality route diagrams of economic benefits are as follows:

(1) R4: C&DW production→Landfill disposal volume of waste→Land loss→Socio-economic losses→C&DW production

R5: C&DW production→Illegal dumping of waste→Land loss→Socio-economic losses→C&DW production.

Increasing the amount of landfill disposal (or illegal dumping of waste) will occupy a large amount of land resources, destroy the soil structure, pollute groundwater resources, and cause economic losses. In order to avoid occupying more land resources and to reduce economic losses, relevant government departments must take measures, such as increasing unit landfill fees and increasing the supervision of illegal dumping and resource-based disposal to reduce the amount of landfill disposal (or illegal dumping) and reduce the output of C&DW.

(2) R6: Total amount of waste sorting and recycling→Fines for illegal dumping→Cost of illegal dumping→Proportion of illegal dumping of waste→Illegal dumping of waste→Illegal dumping and transport volume→Energy consumption of illegal dumping and transport→Greenhouse gas emissions from illegal landfilling of waste→Total greenhouse gas emissions→Global warming→Socio-economic losses→C&DW production→Total amount of waste sorting and recycling.

R6 describes the impact of illegal dumping fines on the total amount of waste sorting and recycling. The continuous growth in C&DW has also prompted some construction units to not treat wastes in accordance with regulations, thereby increasing the amount of illegal dumping of waste. Increasing illegal dumping fines can effectively reduce the amount of illegal dumping of waste and indirectly force contractors to adopt sorting and recycling, thereby increasing the amount of waste sorting and recycling, reducing environmental pollution, and reducing social and economic losses.

(3) R7: C&DW production→Unit landfill cost→ Cost of landfilling of waste→Proportion of landfilling of waste→Landfill disposal volume of waste→Energy consumption of landfilling and transport→Greenhouse gas emissions from landfilling of waste→Total greenhouse gas emissions→Global warming→Socio-economic losses→C&DW production.

R8: C&DW production→Unit landfill cost→ Cost of landfilling of waste→Proportion of landfilling of waste→Ratio of waste sorting and recycling→Total amount of waste sorting and recycling→The amount of waste recovered in the recycling station→Traffic volume of recycled waste in the recycling station→Energy consumption of recycling and transport→Greenhouse gas emissions from waste recycling→Total greenhouse gas emissions→Global warming→Socio-economic losses→C&DW production.

The feedback routes of R7 and R8 describe the reduction in C&DW production by increasing the unit landfill cost. When the unit landfill fee increases, the cost of landfilling increases, the proportion of landfilling decreases, and the greenhouse gas emissions from landfilling can be reduced, thereby reducing the social and economic losses and the production of C&DW. At the same time, increasing the unit landfill fee will also promote contractors to adopt methods of sorting and recycling C&DW. With the increase in sorting and recycling, greenhouse gas emissions from waste will be reduced accordingly, thereby reducing the potential of global warming and socio-economic losses and reducing the production of waste.

### Social benefit analysis

The environmental impact and economic losses caused by the disposal of C&DW have made the relevant government departments aware of the importance of waste recycling, increased the supervision of the illegal dumping of contractors, publicized the economic benefits of waste recycling, and urged the contractors to dispose of the waste as required. The causal feedback from government regulation is shown in R9:

R9: C&DW production→Government supervision→Illegal dumping of waste→Land loss→Socio-economic losses→C&DW production.

Feedback route R9 expresses the impact of government supervision on C&DW production. With the continuous advancement of urbanization, C&DW generated by construction activities is increasing. If supervision is not strengthened, then random stacking and occupation of construction sites will also affect the surrounding environment. In order to prevent the illegal dumping of C&DW, reduce the occupation of limited land resources, and reduce the economic losses caused by illegal landfills, the government has increased the supervision of illegal dumping of C&DW to reduce the amount of illegal dumping, thereby reducing the production of C&DW.

## Simulation analysis of the environmental assessment system model of C&DW: a case study of Guangzhou

On the basis of the relationships among the variables in the causality diagram of the environmental assessment system, by defining all the main variables affecting the process of C&DW disposal, a stock flow diagram of the dynamic model of the C&DW environmental assessment was established, as shown in Fig. 5.

### Data sources

The stock flow diagram of the environmental assessment model of C&DW was mainly constructed on the basis of the causality diagram of the environmental assessment system and the interactions between the internal elements of the system. In order to facilitate the visual quantification of the environmental assessment, in this study, based on the data of the

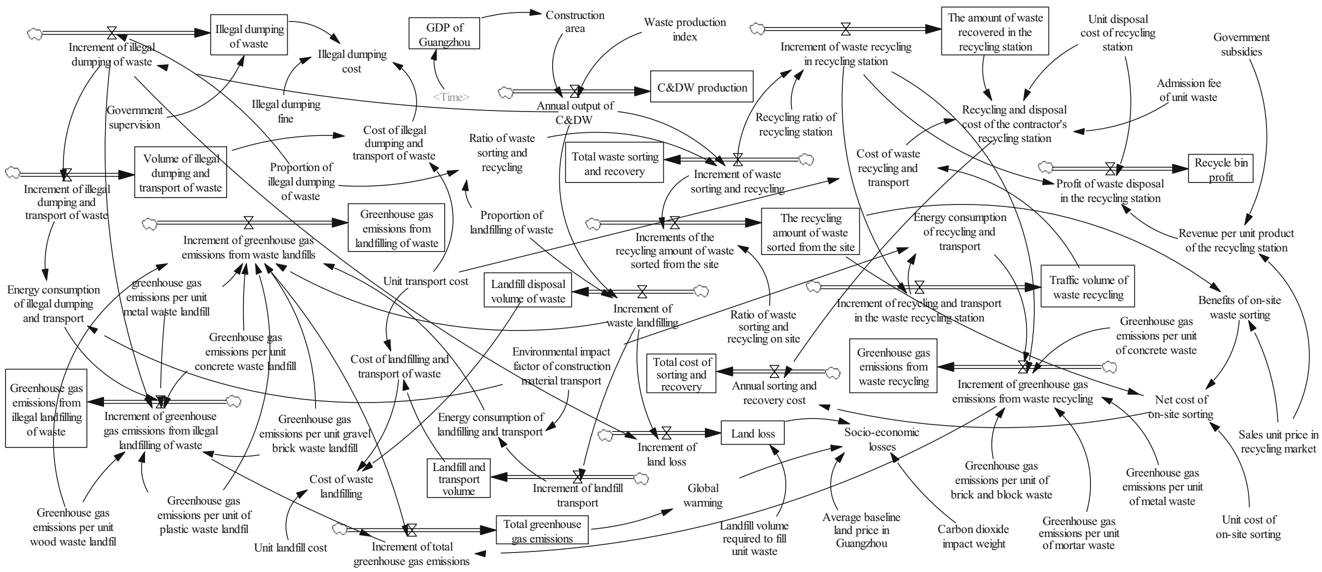



**Fig. 5** Stock flow diagram of the construction and demolition waste environmental assessment model

Guangzhou Statistical Yearbook 2007–2017 and related references, the environmental impact of C&DW disposal in Guangzhou was analyzed through interviews with the Guangzhou Urban Management Committee, Guangzhou Housing and Urban-Rural Construction Committee, and C&DW comprehensive utilization enterprises.

## Equation and parameter setting

The constructed environmental assessment model contained 16 state variables, 6 rate variables, 27 constants, 1 shadow variable, and 21 auxiliary variables. Based on the system stock flow diagram and collected data, the rate, state, and calculation formulas of auxiliary variables involved in the model are shown in Appendix Table 4. The parameters involved were set separately, as shown in Appendix Table 5.

## Model checking

Model testing is a key link to test the reliability and applicability of the constructed model, reasonably reflect objective facts, and ensure that the model can be applied to the development of an environmental assessment of C&DW disposal in Guangzhou. In combination with existing literature studies, the model was checked using the following tests:

1. Dimensional consistency test

Based on the data of the Guangzhou Statistical Yearbook and related literature, a simulation model was established to fit the current situation of environmental assessments of C&DW disposal in Guangzhou. There were no equations with inconsistent dimensions in the model. The two consistencies refer to the consistency of the units on the left and right sides of all the equations in the model. For example, in the equation "cost of waste landfill = unit landfill cost* landfill disposal volume of waste + cost of landfill and transport of waste" the unit at the left side of the equation is 10,000 CNY, while at the right side of the equation, the unit of the landfill fee is CNY/t, the disposal of waste is 10,000 t, and the cost of landfilling and transport of waste is 10,000 CNY. Following the dimensional consistency, the equation "10,000 CNY = CNY/t × 10,000 t + 10,000 CNY" meets the principle of dimensional consistency. In the environmental assessment model of C&DW disposal constructed in this study, all variables and equations passed the dimensional consistency checking function of Vensim software.

2. Validity check

The validity test of the model was used to check whether the results of the simulation were consistent with the actual situation by comparing simulation data with historical data and calculating relative errors. In this study, the validity of the model was verified by comparing the simulation data with the actual values of previous statistical yearbooks. Compared with the construction area from 2013 to 2016, the fitting degree between the actual numerical values and the values of the simulation model is shown in Table 3.

Table 3 shows that the differences between the actual construction area and simulation value in 2015 and 2016 were less than 5%, while in 2013 and 2014, they were less than 14%. The main reason for this was that the large-scale renovation of villages in the city and old towns of Guangzhou in 2013 and

**Table 3** Comparison of actual construction area and simulation values for 2013–2016

| Year | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|
| Actual value (10,000 $m^2$) | 15,056 | 16,399 | 15,160 | 16,290 |
| Simulation value (10,000 $m^2$) | 12,987 | 14,202 | 15,601 | 17,054 |
| Error (%) | 13.7% | 13.4% | 2.9% | 4.7% |

2014 increased the construction area compared with that in the previous 2 years, thereby resulting in a slightly larger error; however, the average error was 8.7%. Therefore, it can be regarded as an effective model. The system can effectively reflect the situation of C&DW disposal in Guangzhou, and other variables can also be simulated by this model.

3. Extreme conditions test

The extreme conditions test was used to determine whether the equation in the model was still meaningful under extreme conditions in the variable definition domain. Selecting the amount of illegal dumping of waste as the dependent variable and government supervision as the independent variable, the extreme conditions of the model were tested. Taking the extreme values of independent variables in the definition domain [0,1], three simulations were conducted according to the values of 0.3 and 0.1 respectively, and the change in the illegal dumping amount of waste was obtained as shown in Fig. 6.

Figure 6 clearly shows that, under two extreme conditions, the reduction in illegal dumping of waste was still meaningful, and the simulation results were consistent with the actual situation. Current 0 indicates that when the government's supervision is equal to 0, the amount of illegal dumping of waste reaches the highest level and is expected to reach 25,437,700 t by 2030. Current 1 refers to the intensity of government supervision of 1, thereby indicating that the regulation of illegal dumping of waste is very strict, so the amount of illegal dumping of waste is 0. Current indicates the value of government supervision under normal circumstances. The value of illegal dumping of waste was between Current 0 and Current 1, which was consistent with the actual situation. According to the same method, the extreme condition test for other variables in the model met the test requirements.

In summary, through the above three tests, the environmental assessment model of C&DW constructed in this study can be used to simulate the environmental impact analysis of C&DW disposal process.

## Model simulation results and discussion

After all variables were input into the model, the values of the main parameters were changed within a reasonable range. The

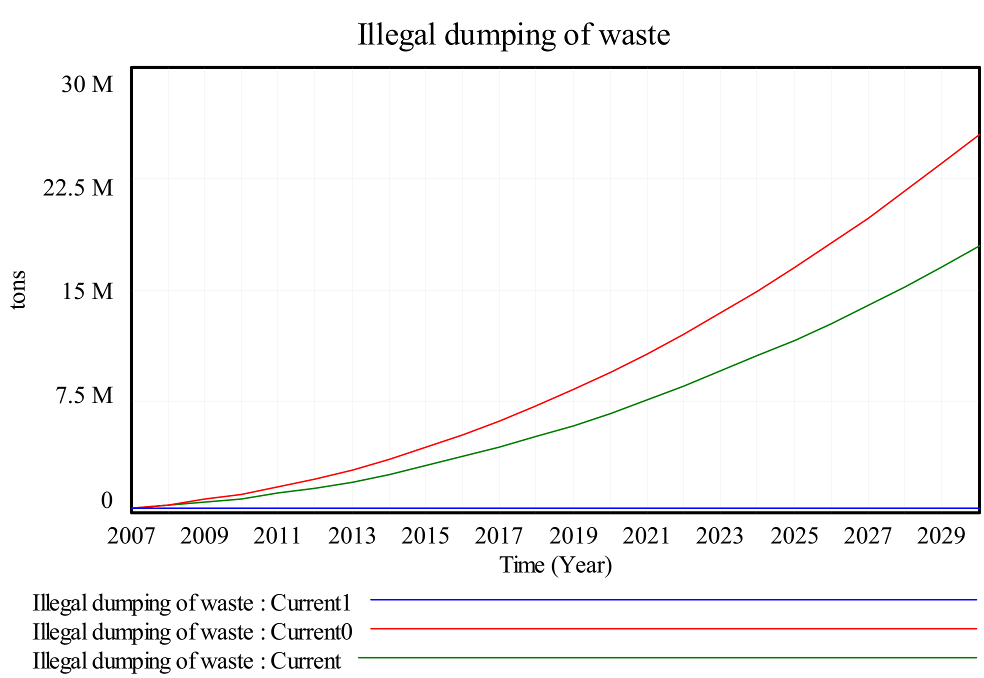



**Fig. 6** Test of extreme conditions for illegal dumping of waste

model was simulated, and different simulation results were recorded and compared. The time of the model was set from 2007 to 2030 with a time step of 1 and units of time of a year.

## Analysis of waste production in various disposal modes

According to the simulation of the model, the amount of illegal dumping, landfill disposal, amount of waste recovered in the recycling station, and the recycling amount of waste sorted from the site in Guangzhou from 2007 to 2030 were obtained, as shown in Fig. 7.

The simulation results in Fig. 7 show that in 2030, the amount of landfill disposal in Guangzhou will reach 80 million tons, and the illegal dumping of waste, the amount of waste recovered in the recycling station, and the amount of waste sorted for recycling from the site will reach nearly 20 million tons. At the same time, they also show that the main method of disposal of C&DW in Guangzhou is landfilling, and the supervision of illegal dumping of waste is not strict. The amount of illegal dumping of waste, the amount of waste recovered in the recycling station, and the amount of waste sorted for recycling from the site are basically the same, and accounting for only 25% of the landfill disposal. In terms of the trend, the growth rate of C&DW production shows no clear signs of declining. With the increase in waste production, the illegal dumping of waste, the amount of waste recovered from the recycling station, and the amount of waste sorted for recycling from the site are also expected to increase slowly and continuously, while the landfill disposal volume will increase significantly, which is caused by the lack of awareness of C&DW reduction and the immaturity of the waste recycling market. As a result, the output of waste is expected to continue to increase significantly, while recycling growth is expected to be slow.

## Simulation analysis of the environmental assessment

The generation and disposal of waste must be accompanied by the impact on the ecological environment. Reasonable disposal methods can reduce environmental pollution, while illegal disposal methods aggravate environmental pollution. The impact of various disposal methods of C&DW on the ecological environment is shown in Fig. 8. Figure 9 shows the greenhouse gas emissions from waste recycling resources, and Fig. 10 shows the total greenhouse gas emissions.

Figure 8 depicts the greenhouse gas emissions from three waste disposal processes, namely, recycling, landfilling, and illegal landfilling. As shown in Fig. 8, because landfilling is the main waste disposal method in Guangzhou, the greenhouse gas emissions from landfilling are the highest. Without effective measures, it is estimated that the greenhouse gas emissions from landfilling will reach 78,541.6 million kg by 2030, followed by illegal landfilling and recycling. Figure 8 shows that the greenhouse gas emissions curve of recycling close to the abscissa and tend to be less than 0. The specific trend is shown in Fig. 9. The greenhouse gas emissions curve of waste recycling in Fig. 9 shows a downward trend with negative values, which

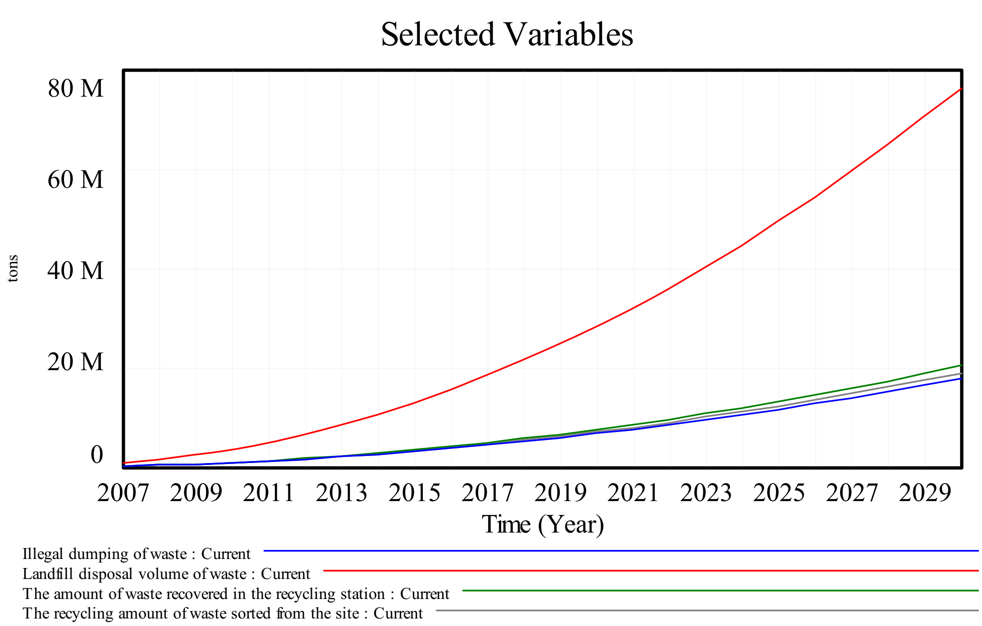
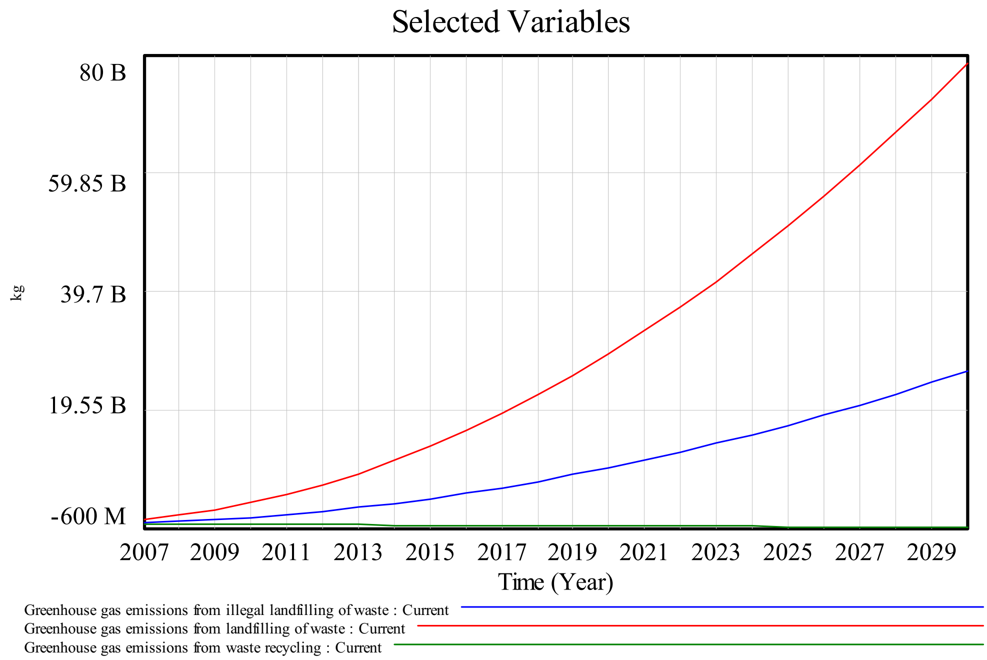


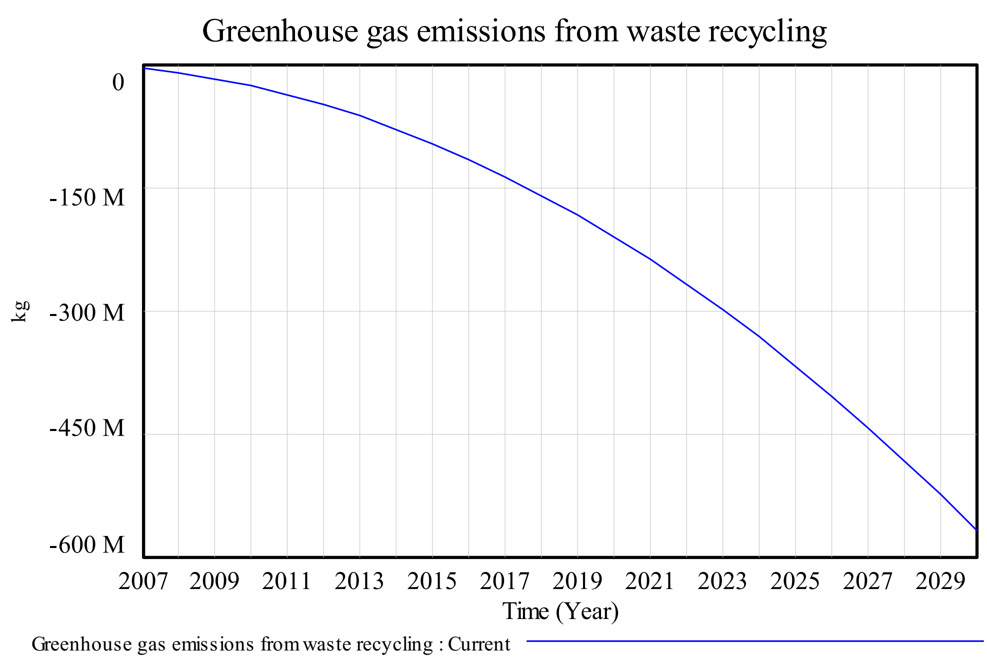

**Fig. 7** Simulation of various disposal methods

**Fig. 8** Simulation model of greenhouse gas emissions from various disposal methods




indicate that with the continuous growth in waste production and the increasingly severe impact on the environment and economy, relevant government departments should be aware of the seriousness of the problem, strengthen waste reduction management, start supporting and promoting green recycled products, encourage recycling, promote low-carbon building materials, conduct technological innovation of recycled products, and urge contractors to adopt resource-based treatment methods in order to reduce greenhouse gas emissions. The downward trend of the curve below 0 indicates that greenhouse gas emissions will be reduced due to recycling. The downward trend represents the annual reduction in greenhouse gas emissions. It was estimated that greenhouse gas emissions with recycling will reach 568.782 million kg by 2030. Compared with the total

**Fig. 9** Simulation of greenhouse gas emissions from waste recycling



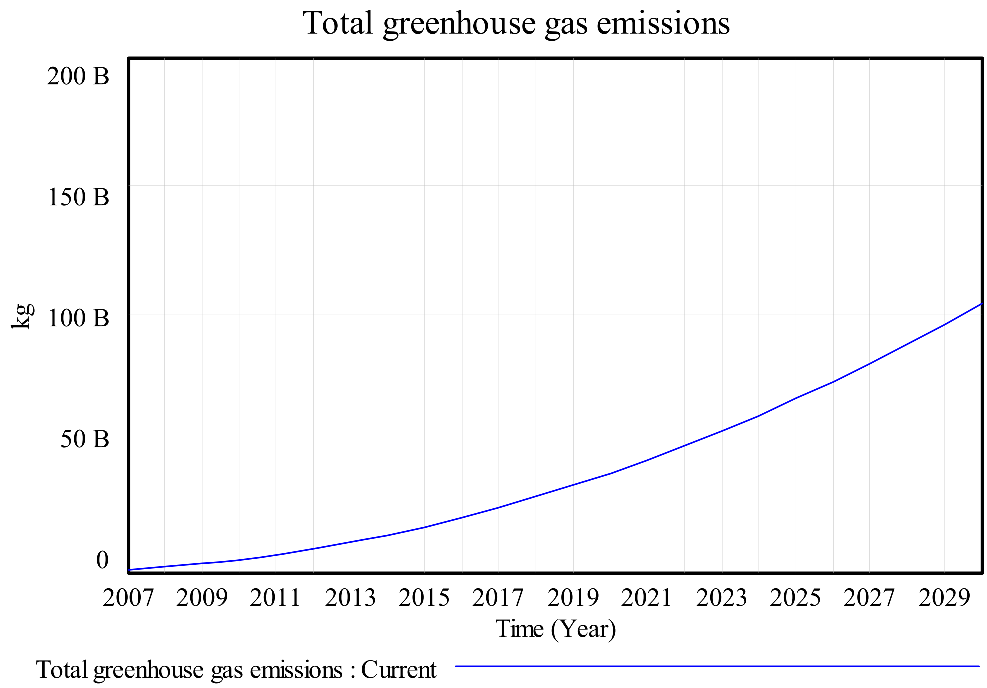



**Fig. 10** Total greenhouse gas emissions

greenhouse gas emissions in Fig. 10, which are as high as 104,163 million kg in 2030, it only accounts for 0.5% of the total emissions. If no reasonable measures are taken to prevent these emissions, they will lead to global warming. Therefore, the government should vigorously support and publicize the recycling of products and improve the resource recycling market so that society can realize the harm of improper disposal of wastes and comprehensively implement a sustainable development strategy.

## Simulation analysis of economic benefit

The cost of waste disposal determines how the contractor disposes of the waste. For the contractor, the method with the lowest cost is the best way to dispose of waste. As shown

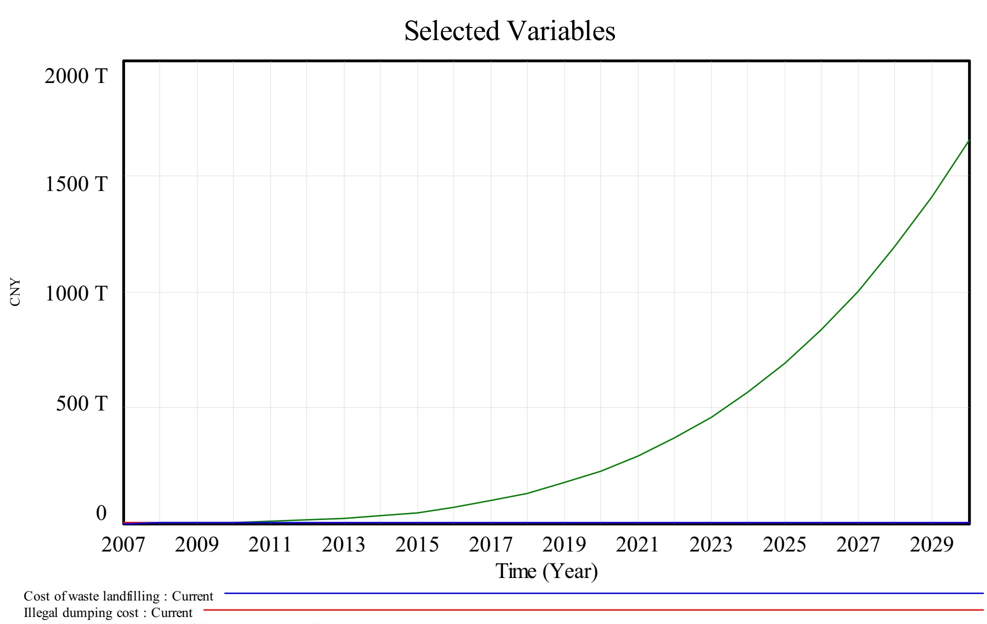



**Fig. 11** Costs of various disposal methods

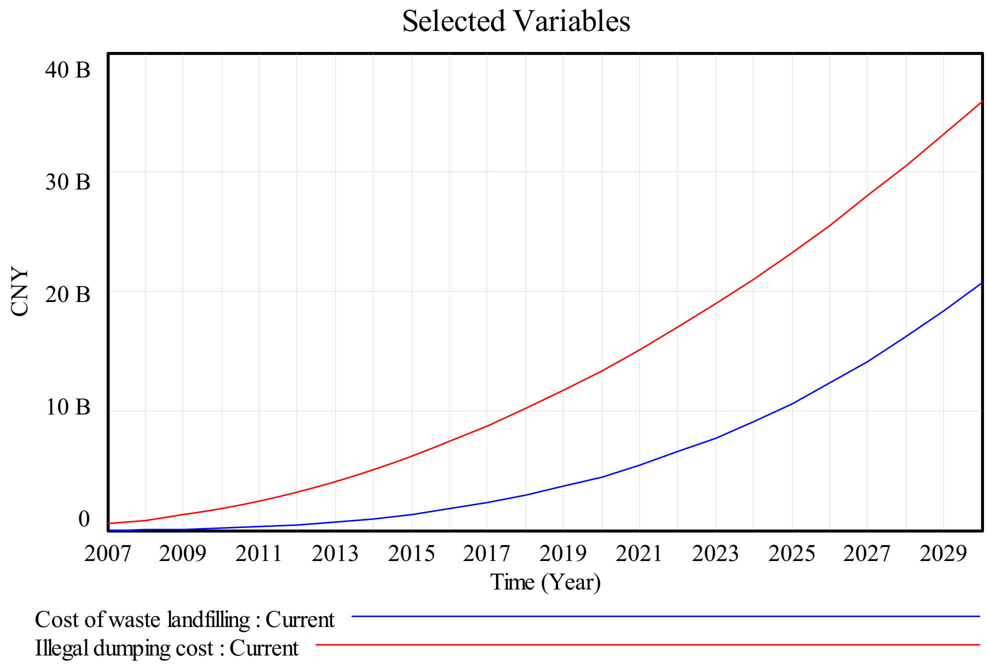



**Fig. 12** Landfilling and illegal dumping costs

in Fig. 11 and Fig. 12, the cost of waste recycling is the highest, followed by the cost of illegal dumping, and finally the cost of landfilling. Because the cost of landfilling is the lowest, many contractors use landfills to dispose of C&DW and reduce costs. In addition, solid waste such as waste earth, waste concrete, bricks, and aggregates can be used for filling foundation pits and for pavement and land reclamation. Since the cost is basically only the transportation cost, it is convenient to handle, and is beneficial to the contractors, the amount of waste disposed of in landfills is expected to increase every year, and the amount recycled is expected to be very small. As shown in Fig. 7, the actual situation was consistent with the simulation results.

Therefore, in order to encourage contractors to recycle waste, relevant government departments should subsidize, relieve, or reduce the relevant taxes and fees for enterprises that adopt recycling treatment, reduce their recycling cost, and encourage more enterprises to use recycling treatment to dispose of C&DW.

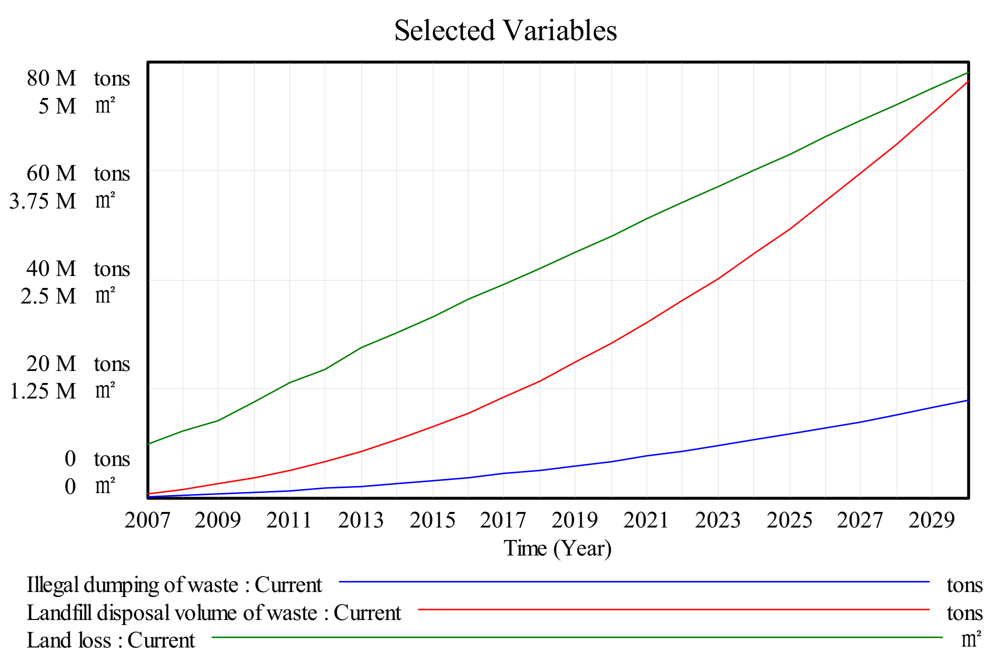



**Fig. 13** The relationships between landfilling, illegal dumping, and land loss

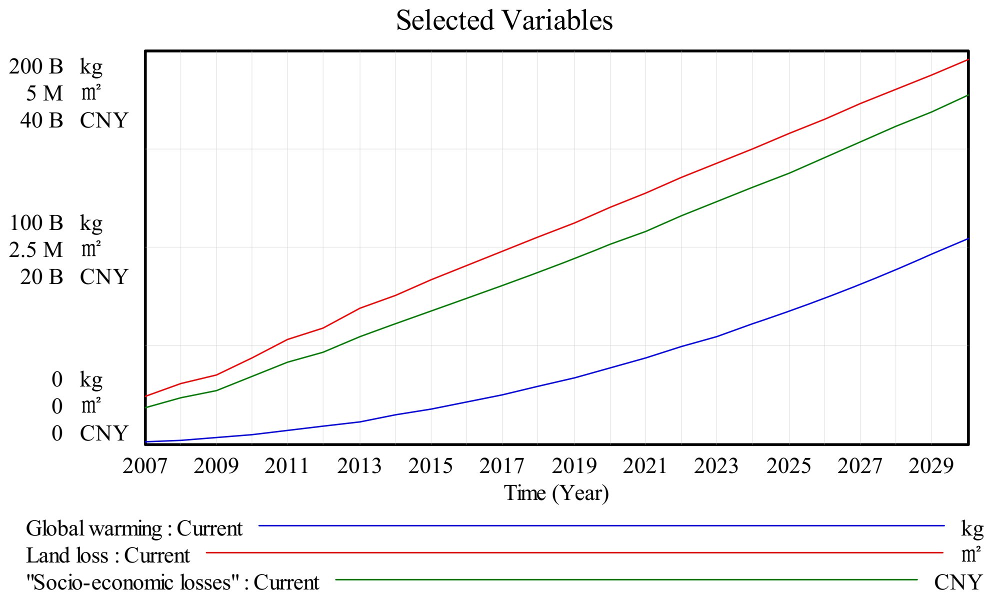



**Fig. 14** The relationships between global warming, land loss, and economic loss

The problem of land pressure caused by C&DW has been the main focus of scholars. As shown in Fig. 13, with the increasing amount of landfill disposal and illegal dumping, especially landfill disposal, the amount of land loss is also increasing each year. The simulation results showed that in 2030, the amount of waste landfill disposal is expected to reach 7631.32 tons and the amount of illegal dumping is expected to reach 1788.3 tons, thereby accounting for about 4.88 million m$^2$ of land. The occupation of such a large area is clearly a large economic loss for Guangzhou, which is an international metropolis with extremely limited land resources available for development. If large areas of land are used to landfill waste, then the situation will likely worsen and seriously hinder the sustainable development of the economy in Guangzhou.

The simulation results in Fig.14 show that the socio-economic losses will increase with the increase in land loss and global warming potential. According to the first allocation and work plan of the carbon emission

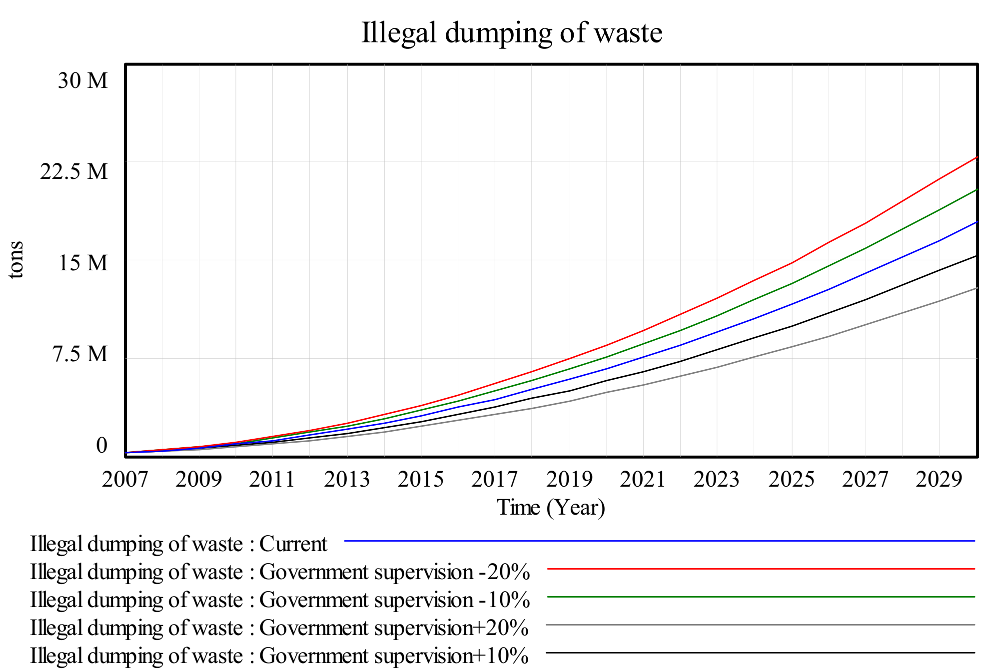



**Fig. 15** The impact of changes in government supervision on illegal dumping

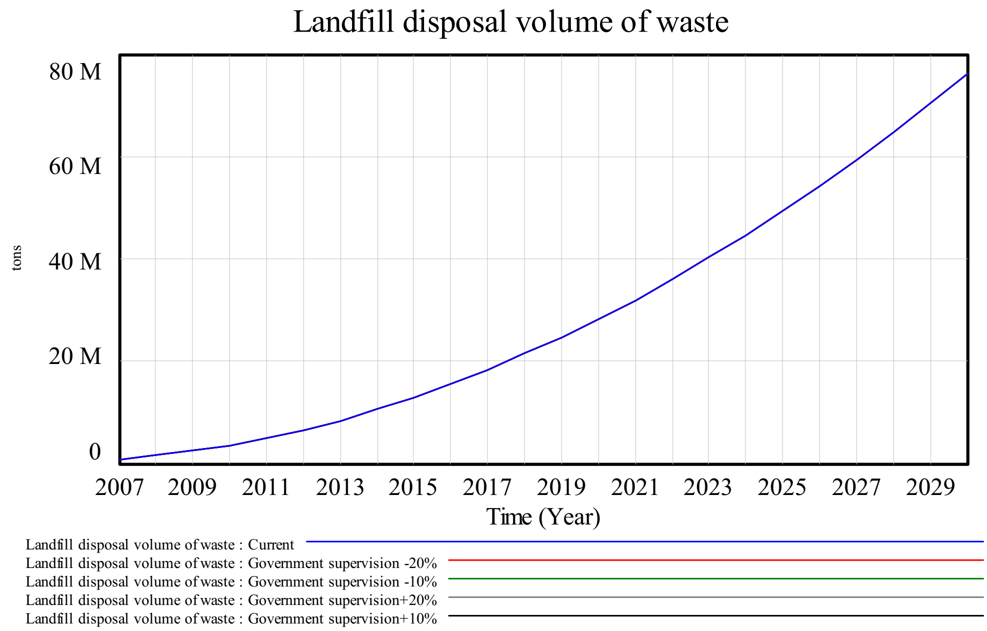



**Fig. 16** Effect of supervision on landfill throughput

quota in Guangdong Province (for trial implementation) and the Guangzhou Municipal Bureau of Land Planning, the weight of the carbon dioxide impact is 0.06 CNY/kg. The benchmark land price levels of commercial service land (first floor land price), office, residential, and industrial land in 11 districts under municipal jurisdiction are 10,602 CNY/$m^2$, 4356 CNY/$m^2$, 7938 CNY/$m^2$, and 988 CNY/$m^2$, respectively. The average benchmark land price is 5971 CNY/$m^2$. According to the current data, the loss caused by land loss and global warming in 2030 will be about 353.8 billion CNY, which is a large loss that is equivalent to the gross national product of a regional city with less developed economy. Guangzhou is developing and renewing rapidly. Many old urban areas are being renovated. If effective measures are not taken to prevent and control land loss and global warming, then the losses after 10 years will be much higher than 353.8 billion CNY. Therefore, the

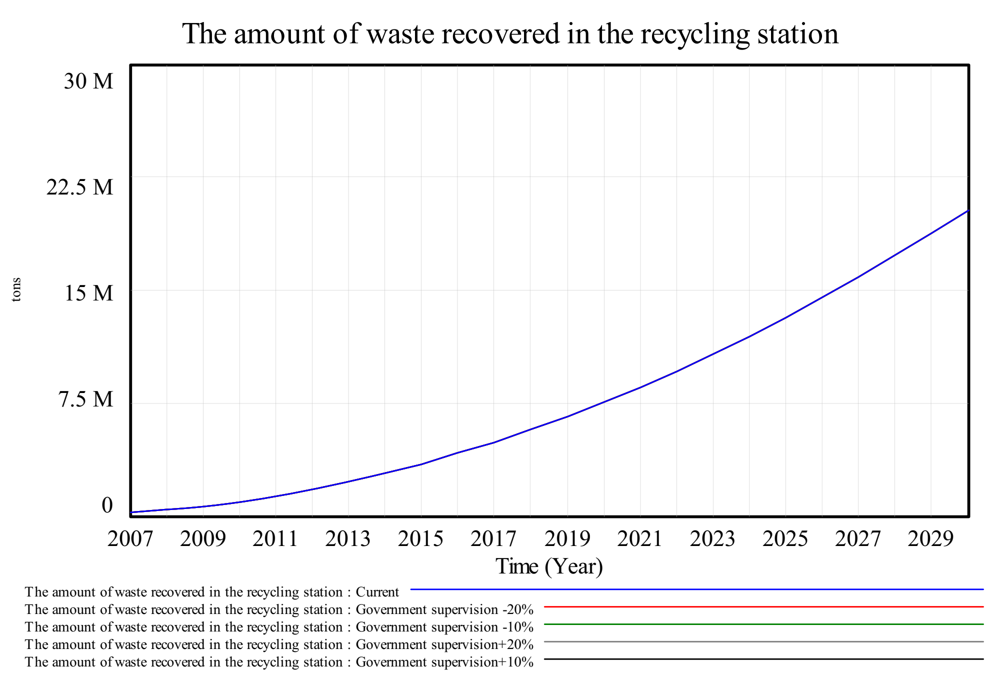



**Fig. 17** Effect of supervision intensity on recycling

relevant government departments should strengthen their supervision and punishment for illegal waste disposal and provide incentives and support to enterprises that recycle waste so as to encourage more construction units to adopt source reduction management and recycling.

### Simulation analysis of social evaluation

Government supervision has an important impact on the amount of illegal dumping of waste. If the supervision is strengthened, then the amount of illegal dumping will decrease, and vice versa. If the intensity of government supervision is changed, it will increase by 10% and 20% and decrease by 10% and 20%, respectively. Observe the influence of the change of government supervision on the amount of illegal dumping of waste. The simulation results of the model are shown in Fig. 15.

The simulation results in Fig. 15 show that if the government strengthens the supervision of illegal dumping, then illegal dumping will show a decreasing trend; if the supervision is weakened, then illegal dumping will increase. If the intensity of government supervision increases by 20%, then illegal dumping will be 12.8464 million tons in 2030, and the severity of the increase will be the lowest; if the intensity of supervision decreases by 20%, then the severity of the increase will be the highest with the dumping amount of 22.915 million tons. Meanwhile, if the intensity of supervision remains unchanged, then the illegal dumping amount will be equal to 17.883 million tons, which would be between the amount from the other two scenarios. Clearly, the intensity of government supervision has a significant impact on the amount of illegal dumping of waste, and the simulation results were consistent with the actual situation. Although the intensity of supervision can significantly reduce the amount of illegal dumping of waste, it has little impact on the output of C&DW. Other measures should be taken to control the output of waste, such as reducing the source, increasing the landfill cost, improving the resource recovery market, encouraging the use of recycled products, and increasing the promotion of assembly buildings.

Government supervision can effectively reduce the illegal dumping of C&DW, but the improvement in waste landfilling and recycling is limited, as shown in Figs. 16 and 17. The figures show that the change in supervision intensity has no significant impact on the amount of landfill disposal and the amount of waste recovered in the recycling station. The trend of graphic changes is basically the same. Thus, there are some limitations in a single policy, which can only affect one aspect and cannot achieve multiple effects. If multiple single policies, such as supervision, fines, subsidies, and fees, are combined to form a mixed policy, then the implementation of a single strategy can be optimized, and the function should be maximized.

## Conclusions

The output of C&DW will not only cause environmental pollution but also affect the sustainable development of the environment, economy, and society. Taking Guangzhou as an example, the impact of the method of C&DW disposal on the environment, economy, and society was evaluated using SD software. Based on the simulation results of the model, several conclusions were drawn. (1) Compared with other disposal methods, the cost of landfilling is relatively low, and solid waste can be used for filling foundation pits, land reclamation, and land leveling. Therefore, at present, landfilling is the main waste disposal method in Guangzhou. (2) Among all waste disposal methods, landfilling has the highest greenhouse gas emissions. It is estimated that the greenhouse gas emissions from landfilling will account for 75% of the total emissions in 2030, while the reduction in greenhouse gas emissions due to recycling will only account for 0.5% of the total emissions, which is very low. (3) Enhanced supervision can significantly reduce the amount of illegal dumping of waste, but the effect on landfill disposal and recycling is not clear, and was basically unchanged. (4) The simulation results showed that according to current data, the land area occupied by waste landfills and illegal dumping in 2030 will be about 4.88 million $m^2$, and the economic losses caused by land loss and global warming will account for 9.1% of Guangzhou's GDP in 2030, which is equivalent to the GDP of a regional city with a less developed economy. This will not only aggravate the pressure of land shortage and environmental pollution, but also cause large economic losses and seriously hinder the sustainable development strategy. In view of the existing waste management problems in Guangzhou, the following suggestions were introduced.

1. Developing green building materials and building a green-oriented urban design. The average energy consumption of building products in China is much higher than that in developed countries. There is a large area for improvement in the energy efficiency of building materials. When purchasing building materials, priority should be given to recyclable or renewable materials to improve the recycling efficiency of building materials and reduce energy consumption. Green building materials can not only reduce the use of natural resources and energy but also promote the recycling industry to actively

recycle waste and produce recyclable, radiation-free building materials with low (or no) pollution. Advocating the development of new green building materials not only saves energy and reduces carbon dioxide emissions from building materials in production and waste disposal but also improves the structure's thermal insulation and other functions and reduces carbon dioxide emissions from buildings in the operation process. The low-carbon building policy system and the relatively lagging policy support should be improved. The research and development of new energy-saving building materials should be vigorously supported, and the research and development of green building materials should be financially supported.

2. Promoting assembly building, green building, and recycled products. The government should vigorously promote assembly building, advocate green building, conduct research on low-carbon materials technology, encourage construction units to use recycled products, and reduce waste production from the source. In accordance with the requirements of promoting supply-side structural reform and new urbanization development in China, vigorously developing assembly buildings such as steel structures and concrete has the advantages of developing new energy-saving and environmental protection industries, improving the level of building safety, promoting the resolution of excess capacity, and promoting the adjustment and upgrading of industrial structures, which also meets the requirements of green buildings.
3. Promoting the development of construction and demolition waste industries and optimizing market interest-driven mechanisms by policies. China has not paid enough attention to the recycling of C&DW, mainly because there is no mature market and the relevant enterprises do not see the considerable benefits of recycling waste. The sustainable development strategy should be implemented in the C&DW recycling industry, and the government should provide encouragement and support for its development. Green passage should be set up for enterprises or construction units that adopt resource recycling, economic stimulus policies should be implemented, taxes should be reduced and preferential measures for water, and electricity should be provided to stimulate the enthusiasm of producers. LCA and management of C&DW should be strengthened. Macro-control of the recycling market should be conducted to support green industries and provide power for the development of the recycling industry.
4. Publicizing the recycling of waste materials and raising citizens' awareness of environmental protection and knowledge of green building. China should vigorously publicize the recycling of waste resources, promote recycled building materials, and enhance the public's awareness of environmental protection and knowledge of recycled building materials so that citizens can understand the green benefits of recycled building materials and green buildings. Through advertising, the misunderstanding of the waste recycling industry can be eliminated and the sense of identity can be improved, which is conducive to the development of recycled building materials and the recycling industry and to the implementation of a sustainable development strategy.
5. Adopting a mixed policy to manage construction and demolition waste. Increasing government supervision can effectively reduce the amount of illegal dumping of waste, but it has little impact on landfill disposal and recycling. There are some limitations to a single policy, which can only affect one aspect, but cannot achieve multiple effects. If the integration of multiple single policies, such as supervision, fines, subsidies, and fees, can optimize the implementation of a single strategy, then it should be able to maximize its functions. That is to say, while increasing supervision, waste landfill fees and illegal dumping fines should also be increased, and subsidies for construction units and resource recovery companies that use recycled products should be increased. Combining a single policy into a mixed policy can achieve greater benefits than those of a single policy.

In this study, Vensim software was used to simulate and analyze the environmental assessment system of C&DW disposal in Guangzhou and was combined with economic and social evaluation. This provided a reference for reasonable disposal of C&DW in Guangzhou and can also help other cities to solve the problem of waste impact. However, there were some limitations in this study as only the waste generated in the construction process of new projects, was considered, and not that of demolition and decoration. At the same time, the simulation of government participation in the system was insufficient. In waste disposal, many aspects require compulsory government participation, such as increasing charges for construction waste discharge, increasing the waste utilization rate, and other policies. However, in the model, only monitoring efforts were considered, and simulation analysis of mixed policies was lacking, which needs to be improved in future research.

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## Appendix 1

**Table 4** Variables and equations of the construction and demolition waste (C&DW) environmental assessment model

| S/N | Variables | Equation |
|---|---|---|
| 1 | GDP of Guangzhou | WITH LOOKUP(time)Lookup = ([(2007, 0) − (2030, 40,000)] (2007, 7140),…,(2030, 39,053)) |
| 2 | Construction area | (1.004 × GDP of Guangzhou-2571.99) × 10,000 (Note) |
| 3 | Increment of illegal dumping of waste | Annual output of C&DW × proportion of illegal dumping of waste |
| 4 | Illegal dumping of waste | Increment of illegal dumping of waste × (1 − government supervision) |
| 5 | Increment of illegal dumping and transport of waste | Increment of illegal dumping of waste |
| 6 | Energy consumption of illegal dumping and transport | Environmental impact factor of construction material transport × increment of illegal dumping and transport of waste |
| 7 | Increment of greenhouse gas emissions from illegal landfilling of waste | (Greenhouse gas emissions per unit plastic waste landfill + greenhouse gas emissions per unit wood waste landfill + greenhouse gas emissions per unit concrete waste landfill + greenhouse gas emissions per unit gravel brick waste landfill + greenhouse gas emissions per unit metal waste landfill) × increment of illegal dumping of waste + energy consumption of illegal dumping and transport |
| 8 | Annual output of C&DW | Construction area × waste production index |
| 9 | Cost of illegal dumping and transport of waste | Unit transport cost × volume of illegal dumping and transport of waste |
| 10 | Illegal dumping cost | Illegal dumping of waste × illegal dumping fine + cost of illegal dumping and transport of waste |
| 11 | Cost of waste landfilling | Unit landfill cost × landfill disposal volume of waste + cost of landfilling and transport of waste |
| 12 | Cost of landfilling and transport of waste | Unit transport cost × landfill and transport volume |
| 13 | Increment of total greenhouse gas emissions | Increment of greenhouse gas emissions from illegal landfilling of waste + increment of greenhouse gas emissions from waste landfills + increment of greenhouse gas emissions from waste recycling |
| 14 | Increment of waste sorting and recycling | Annual output of C&DW × ratio of waste sorting and recycling |
| 15 | Ratio of waste sorting and recycling | 1 − (proportion of landfill of waste + proportion of illegal dumping of waste) |
| 16 | Increment of greenhouse gas emissions from waste landfills | (Greenhouse gas emissions per unit plastic waste landfill + greenhouse gas emissions per unit wood waste landfill + greenhouse gas emissions per unit concrete waste landfill + greenhouse gas emissions per unit gravel brick waste landfill + greenhouse gas emissions per unit metal waste landfill) × increment of waste landfill + energy consumption of landfill and transport |
| 17 | Increment of waste landfilling | Proportion of landfill of waste × proportion of landfill of waste |

**Table 4** (continued)

| S/N | Variables | Equation |
|---|---|---|
| 18 | Annual sorting and recovery cost | Recycling and disposal cost of contractor recycling station + net cost of site sorting |
| 19 | Increment of landfill transport | Increment of waste landfilling |
| 20 | Energy consumption of landfilling and transport | Environmental impact factor of construction material transport × increment of landfill transport |
| 21 | Increment of waste recycled in recycling station | Increment of waste sorting and recycling × recycling ratio of recycling station |
| 22 | Increment of the recycling amount of waste sorted from the site | Increment of waste sorting and recycling × ratio of waste sorting and recycling on site |
| 23 | Increment of recycling and transport in waste recycling station | Increment of waste recycled in recycling station |
| 24 | Increment of greenhouse gas emissions from waste recycling | (Greenhouse gas emissions per unit of concrete waste + greenhouse gas emissions per unit of mortar waste + greenhouse gas emissions per unit of brick and block waste + greenhouse gas emissions per unit of metal waste) × increment of recycled waste in recycling station + energy consumption of recycling and transport |
| 25 | Land loss | Increment of land loss × landfill volume required to fill unit waste |
| 26 | Global warming | Total greenhouse gas emissions |
| 27 | Socio-economic losses | Global warming × carbon dioxide impact weight + average baseline land price in Guangzhou × land loss |
| 28 | Recycling and disposal costs of the contractor's recycling station | (Cost of waste recycling and transport + unit disposal cost of recycling station + admission fee of unit waste) × the amount of waste recovered in the recycling station |
| 29 | Cost of waste recycling and transport | Unit transport cost × traffic volume of waste recycling |
| 30 | Profit of waste disposal in the recycling station | (Revenue per unit product of recycling station − unit disposal cost of recycling station) × increment of waste recycling in recycling station |
| 31 | Energy consumption of recycling and transportation | Environmental impact factor of construction material transport × increment of recycling and transport of waste recycling station |
| 32 | Revenue per unit product of the recycling station | Sales unit price in recycling market + government subsidies |
| 33 | Benefits of on-site waste sorting | Sales unit price in recycling market × the recycling amount of waste sorted from the site |
| 34 | Net cost of on-site sorting | Benefits of on-site waste sorting- unit cost of on-site sorting × the recycling amount of waste sorted from the site |

Reference Liu et al. (2014); using IBM SPSS Statistics software, the linear regression equation between the construction area (unit: $m^2$ ) and GDP was obtained

## Appendix 2

**Table 5** Setting of relevant parameters of the construction and demolition waste environmental assessment model

| S/N | Name of parameters | Assignment | Data source |
|---|---|---|---|
| 1 | Fines for illegal dumping | 2000 CNY/t time | Liu et al. (2014); Liu et al. (2019a) |
| 2 | Government supervision | 0.3 dmnl (0–1) | Interview survey |
| 3 | Proportion of illegal dumping of waste | 0.15 dmnl | Wang et al. (2014); Bao et al. (2019) |
| 4 | Ratio of waste sorting and recycling in site | 424.49 kg/t | Zhang et al. (2010) |
| 5 | Greenhouse gas emissions per unit of plastic waste landfill | 514.54 kg/t | Zhang et al. (2010) |
| 6 | Greenhouse gas emissions per unit of gravel and brick waste landfill | 4.2 kg/t | Zhang et al. (2010) |
| 7 | Greenhouse gas emissions per unit of concrete waste landfill | 43.99 kg/t | Zhang et al. (2010) |
| 8 | Greenhouse gas emissions per unit of metal waste landfill | 37.82 kg/t | Zhang et al. (2010) |
| 9 | Unit transport cost | 4 CNY/t | Interview survey |
| 10 | Unit landfill fee | 30 CNY/t | Wang et al. (2016) |
| 11 | Recycling ratio of recycling station | 0.3 dmnl | Wang et al. (2016) |
| 12 | Proportion of landfilling of waste | 0.45 dmnl | Rodríguez et al. (2007) |
| 13 | Ratio of waste sorting and recycling on site | 0.28 dmnl | Yuan and Wang (2014) |
| 14 | Unit area of land occupied by landfill | 0.6 t/m$^2$ | Poon et al. (2001) |
| 15 | Unit disposal cost of recycling station | 40 CNY/t | Interview survey |
| 16 | Admission fee of unit waste | 3 CNY/t | Hu and Zhou (2018) |
| 17 | Government subsidies | 25 CNY/t | Liu et al. (2014) |
| 18 | Sales unit price in recycling market | 40 CNY/t | Chen and Yuan (2017) |
| 19 | Unit cost of on-site sorting | 20 CNY/t | Yuan (2017) |
| 20 | Greenhouse gas emissions per unit of concrete waste | 1.1365 kg/t | Wang et al. (2018a, b); Liu et al. (2019b) |
| 21 | Greenhouse gas emissions per unit of metal waste | −37.3142 kg/t | Wang et al. (2018a, b) |
| 22 | Greenhouse gas emissions per unit of mortar waste | 0.297 kg/t | Wang et al. (2018a, b); Mak et al. (2019) |
| 23 | Greenhouse gas emissions per unit of brick and block waste | 27.902 kg/t | Wang et al. (2018a, b) |
| 24 | Average baseline land price in Guangzhou | 5971 CNY/m$^2$ | GZLRPC (2017) |
| 25 | Carbon dioxide impact weight | 0.06 CNY/kg | GZCEE (2013) |
| 26 | Index of waste production | 0.037 t/m$^2$ | Wang et al. (2012) |
| 27 | Environmental impact factor for transportation of building materials | 4.169 kg/t | Wang et al. (2014) |

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